

X-ray Spectral States and High-Frequency QPOs in Black Hole Binaries

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Abstract. The high-frequency quasi-periodic oscillations (HFQPOs) in the X-ray emission of black hole binaries and candidates are briefly reviewed with respect to the question of X-ray states. We use the prescription of McClintock and Remillard (2005), in which X-ray spectra and power density spectra are used to differentiate three main states of active accretion: "thermal", "hard", and "steep power-law". Respectively, each state emphasizes a different physical element that may contribute radiation: the accretion disk, a jet, and a compact non-thermal corona. We focus on the four sources that exhibit pairs of HFQPOs with frequencies that scale in a 3:2 ratio. All of these HFQPOs are associated with the steep power-law (SPL) state. Furthermore, there is a clear trend in which the $2\nu_0$ oscillation is seen when the source has high X-ray luminosity, while the $3\nu_0$ QPO is seen at lower luminosity.

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1. X-ray States of Black Hole Binaries

The X-ray states of black hole binaries have been defined (McClintock and Remillard 2005) in terms of quantitative criteria that utilize both X-ray energy spectra and power density spectra (PDS). This effort follows the lessons of extensive monitoring campaigns with the *Rossini* X-ray Timing Explorer (*RXTE*), which reveal the complexities of X-ray outbursts in black-hole binary systems and candidates (e.g. Sobczak et al. 2000; Homan et al. 2001). These definitions of X-ray states utilize four criteria: f_{disk} , the ratio of the disk flux to the total flux (both unabsorbed) at 2–20 keV; the power-law photon index (Γ) at energies below any break or cutoff; the integrated rms power (r) in the PDS at 0.1–10 Hz, expressed as a fraction of the average source count rate; and the integrated rms amplitude (a) of a quasi-periodic oscillation (QPO) detected in the range of 0.1–30 Hz. PDS criteria (a and r) are evaluated in a broad energy range, e.g. the full bandwidth of the *RXTE* PCA instrument, which is effectively 2–30 keV.

The energy spectra of accreting black holes often exhibit composite spectra consisting of two broadband components. There is a multi-temperature accretion disk (Makishima et al. 1986; Li et al. 2005) and a power-law component (Zdziarski and Gierlinski 2004). The thermal state designation selects observations in which the spectrum is dominated by the heat from the inner accretion disk. The thermal state (formerly the

"high/soft" state) is defined by the following three conditions: $f > 0.75$; there are no QPOs with $a > 0.005$; $r < 0.06$.

There are two types of non-thermal spectra (Grove et al. 1998), and they are primarily distinguished by the value Γ . There is a hard state with $\Gamma \sim 1.7$, usually with an exponential decrease beyond ~ 100 keV. The **hard state** is associated with a steady type of radio jet (Gallo et al. 2003; Fender 2005). In terms of X-ray properties, the hard state is also defined with three conditions: $f < 0.2$; $1.5 < \Gamma < 2.1$; $r > 0.1$. In the hard state, the accretion disk spectrum may be absent, or it may appear to be usually cool and large.

The other non-thermal state is associated with strong emission from a steep power-law component ($\Gamma \sim 2.5$), with no apparent cutoff (Grove et al. 1998). This component tends to dominate black-hole binary spectra when the luminosity approaches the Eddington limit. Thermal emission from the disk remains visible during the SPL state. Low-frequency QPOs (LFQPOs), typically in the range 0.1–20 Hz, are frequently seen when the flux from the power law increases to the point that $f < 0.8$. The SPL state (formerly the "very high" state) is defined by: (1) $\Gamma > 2.4$, (2) $r < 0.15$, and (3) either $f < 0.8$, while an LFQPO is present with $a > 0.01$, or $f < 0.5$ with no LFQPOs.

The temporal evolution of X-ray states for GRO J1655–40 (1996–1997 outburst), XTE J1550–564 (1998–1999 outburst), and GX339–4 (several outbursts) are illustrated by Remillard (2005). Two of these examples display the op-

posite extremes of the complexity in black-hole outbursts. GRO J1655–40 shows a simple pattern of spectral evolution in which the thermal and SPL states evolve in proportion to luminosity, while XTE J1550–564 shows complex behavior and intermediate states, in which there is a range of luminosity that is occupied by all states. This is interpreted as strong evidence that the primary variables for understanding the energetics of accretion must include variables in addition to the black hole mass and the mass accretion rate.

2. High-Frequency QPOs from Black Hole Binaries

High-frequency QPOs (40–450 Hz) have been detected thus far in 7 black-hole binaries or candidates (see McClintock and Remillard 2005 and references therein). These are transient and subtle oscillations, with $0.5\% < a < 5\%$. The energy dependence of a is more like the power-law spectrum than the thermal spectrum, and some of the QPOs are only detected with significance in hard energy bands (e.g. 6–30 keV or 13–30 keV). For statistical reasons, some HFQPO detections additionally require efforts to group observations with similar spectral and/or timing characteristics.

Four sources (GRO J1655–40, XTE J1550–564, GRS 1915+105, and H1743–322) exhibit pairs of QPOs that have commensurate frequencies in a 3:2 ratio (Remillard et al. 2002; Homan et al. 2005; Remillard et al. 2005; McClintock et al. 2005). All of these HFQPOs have frequencies above 100 Hz. The observations associated with a particular QPO may vary in X-ray luminosity by factors (max/min) of 3 to 8. This supports the conclusion that HFQPO frequency systems are a stable signature of the accreting black hole. This is an important difference from the kHz QPOs in neutron-star systems, which show changes in frequency when the luminosity changes. Finally, for the three (of four) cases where black hole mass measurements are available, the frequencies of HFQPO pairs are consistent with a M^{-1} dependence (McClintock and Remillard 2005; $\nu_0 = 931 M^{-1}$). This result is generally consistent with oscillations that originate from effects of GR, with an additional requirement for similar values in the dimensionless BH spin parameter. Thus, black hole HFQPOs with 3:2 frequency ratio may provide an invaluable means to constrain black hole mass and spin via GR theory.

Commensurate HFQPO frequencies can be seen as a signature of an oscillation driven by some type of resonance condition. Abramowicz and Kluzniak (2001) had proposed that QPOs could represent a resonance in the coordinate frequencies given by GR for motions around a black hole under strong gravity. Earlier work had used GR coordinate frequencies and associated beat frequencies to explain QPOs with variable frequencies in both neutron-star and black-hole systems (Stella et al. 1999), but without a resonance condition.

Current considerations of resonance concepts include more realistic models which are discussed in detail elsewhere in these proceedings. The “parametric resonance” concept (Kluźniak et al. 2004; Török et al. 2004) describes oscillations rooted in fluid flow where there is coupling between the

radial and polar GR frequencies. There is also a resonance model tied to asymmetric structures (e.g. a spiral wave) in the inner disk (Kato 2005). Another alternative is to consider that state changes might thicken the inner disk into a torus, where the normal modes under GR (with or without a resonance condition) can yield oscillations with a 3:2 frequency ratio (Rezzolla et al. 2003; Fragile 2005). Finally, one recent MHD simulation reports evidence for resonant oscillations (Kato 2004). This research will be studied vigorously, while more than one model might be relevant for the different types of QPOs in accreting BH and NS systems.

3. High-Frequency QPOs and the SPL State

A study of the HFQPOs in GRO J1655–40 and XTE J1550–564 has shown that detections in individual observations are associated with the SPL state (Remillard et al. 2002). In Figs. 1 and 2, this point is made more clearly by comparing HFQPO detections to X-ray state classifications that utilize the criteria of McClintock and Remillard (2005). Each plot displays an energy diagram, where the flux from the accretion disk is plotted versus the flux from the power-law component. The flux is determined from the parameters obtained from spectral fits. Here the flux is integrated over the range of 2–20 keV, which is the band used to define X-ray states. It has been shown that the results can also be displayed in terms of bolometric fluxes without changing the conclusions (Remillard et al. 2002).

In the left panels of Figs. 1 and 2, the X-ray state of each observation is noted via the choice of the plotting symbol. The state codes are: thermal (red x), hard (blue square), SPL (green triangle), and any intermediate type (yellow circle). The 1996–1997 outburst of GRO J1655–40 (Fig. 1, left) is mostly confined to the softer X-ray states (i.e. thermal and SPL). On the other hand, observations of XTE J1550–564 (Fig. 2, left) show far greater complexity, with a mixture of states for a wide range in luminosity. These data combine the 1998–1999 and 2000 outbursts of the source, since HFQPOs are seen during both outbursts. The determinations of fluxes follows the same procedures described for GRO J1655–40.

The right panels of Figs. 1 and 2 show the same data points, but the choice of symbols is related to the properties of HFQPOs. Observations without HFQPO detections are shown with a black “x”. HFQPO detections are distinguished for frequency: $2\nu_0$ oscillations (blue squares), $3\nu_0$ oscillations (blue star). For GRO J1655–40 (only), there are three observations that show both $2\nu_0$ and $3\nu_0$ HFQPOs, and the data are shown with filled blue circles. Comparisons of the left and right panels of Figs. 1 and 2 show that HFQPO detections for the two sources are all obtained during the SPL state. These figures also display the clear association of $2\nu_0$ HFQPOs with higher luminosity in the power-law component, while $3\nu_0$ HFQPOs occur at lower luminosity, as has been reported previously (Remillard et al. 2002).

The HFQPO detections with a 3:2 frequency ratio for the other two BH sources require more complicated data selections, and so we cannot compare X-ray states and HFQPO properties in the same manner. In the case of H1743–322,

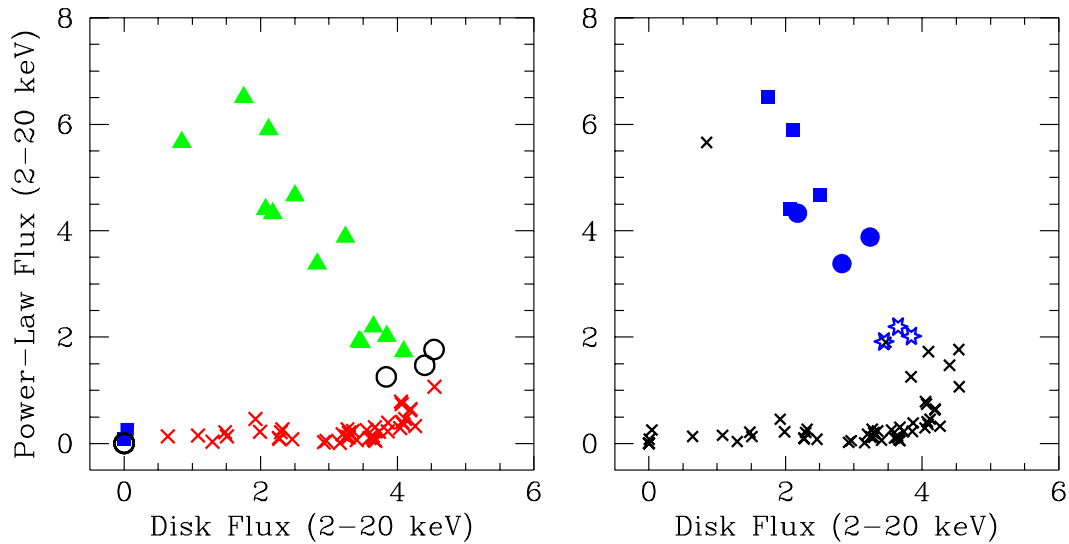


Fig. 1. X-ray states and HFQPOs during the 1996-1997 outburst of GRO J1655-40. The left panel shows the energy diagram, where flux from the accretion disk is plotted versus flux from the power-law component. Here, the symbol type denotes the X-ray state: thermal (red “x”), hard (blue square), steep power-law (green triangle), and any type of intermediate state (yellow circle). The right panel shows the same data points, while the symbol choice denotes HFQPO detections: 300 Hz (blue squares), 450 Hz (blue star), both HFQPOs (blue circle), and no HFQPO (black “x”). The HFQPO detections are clearly linked to the SPL state, and the HFQPO frequency is clearly correlated with power-law luminosity.

there are very few HFQPO detections in individual observations (Homan et al. 2005; Remillard et al. 2005). However, the technique used to combine observations to gain some of the HFQPO detections at $2\nu_0$ and $3\nu_0$ utilized SPL classifications grouped by luminosity level. The success of this strategy shows that H1743-322 follows the same patterns displayed in Figs. 1 and 2. In GRS1915+105, the HFQPO pair with 3:2 frequency ratio involves extraction of oscillations from portions of two different modes of unstable light curves with cyclic patterns of variability. Further analysis is required to produce the energy diagrams for these data.

There are undoubtedly statistical issues to consider in judging the absence of HFQPOs in Figs. 1 and 2, since most detections are near the detection limit (i.e. $3-5\sigma$). Nevertheless, efforts to group observations in the hard and thermal states, in order to lower the detection threshold, routinely yield null results at either the known or random HFQPO frequencies. We conclude that the models for explaining HFQPO frequencies must also explain the geometry, energetics, and radiation mechanisms for the SPL state.

4. Spectral states, QPO, modulation of X-rays

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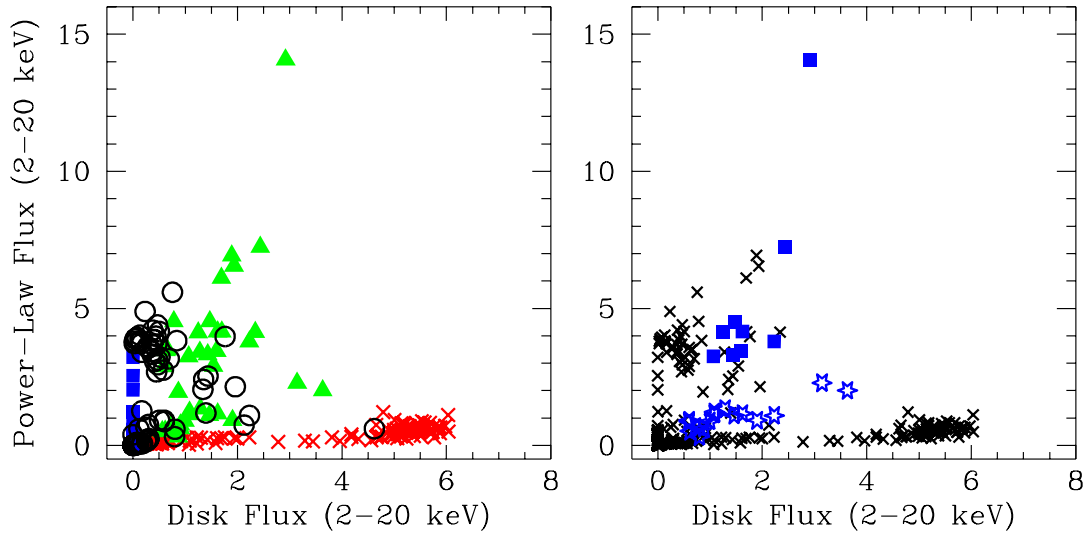


Fig. 2. X-ray states and HFQPOs during the 1998-1999 and 2000 outbursts (combined) of XTE J1550-564. The left panel shows the energy diagram, with plotting symbol chosen to denote the X-ray state, as in Fig. 1. The right panel shows frequency-coded HFQPO detections: near 184 Hz (blue squares), near 276 Hz (blue star), and no HFQPO (black “x”). Again, HFQPO detections are linked to the SPL state, and the HFQPO frequency is correlated with power-law luminosity.

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